Outline:
- AGN-galaxy co-evolution through feedback: results
- perspectives from ground and space
- NOEMA: next IRAM array
Through which path does the common growth occur?

- **Merging**
  - Galaxy
  - MBH
    - accretion
- **Feedback**
  - Stellar / SN
  - AGN

Volonteri 2012, Science
The merging sequence

Two Spirals  The Antennae  NGC 6240  Elliptical Galaxy
Merging nuclear supermassive BHs

When galaxies merge their nuclear MBHs also merge

Menci et al. 2003:
- merging histories of the DM clumps imply that $M_{\text{gas}} \sim \sigma^{2.5}$
- destabilization of $M_{\text{gas}}$ by interactions steepens by another $\sigma$
- SN feedback depletes the residual gas shallow potential wells, further steepening the correlation.

Peng 2007:
- galaxy merging average out extreme values of $M_{\text{BH}}/M_*$, converging toward a narrow correlation

Jahnke & Maccio 2010:
- number of mergers consistent with that of standard merger trees models for the formation of galaxies (and SMBH)
Galaxy - Massive Black Hole growth

- Merging
  - Galaxy
  - MBH
    - accretion
- Feedback
  - Stellar / SN
  - AGN

Volonteri 2012, Science
AGN feedback

- AGN heat ISM stopping star formation and accretion

Without AGN heating SAMs:
1. overpredict luminosities of massive galaxies by ~2 mags
   and/or
2. predict a number of massive blue galaxies higher than observed

Menci et al. 2006, Croton+2006, Millenium

AGN feedback could be the solution. Observations of feedback in action can confirm.
AGN Feedback & AGN accretion mode

Quasar mode
- Major mergers
- Minor mergers
- Galaxy encounters
- Activity periods are strong, short and recurrent
- AGN density decrease at $z<2$ is due to:
  - Decrease with time of galaxy merging rate
  - Decrease with time of encounters rate
  - Decrease with time of galactic cold gas left available for accretion
- Feedback is driven by AGN radiation

Radio mode
- Low accretion-rate systems tend to be radiatively inefficient and jet-dominated
- Low level activity can be ~continuous
- Feedback from low luminosity AGN dominated by kinetic energy
  
  Croton+ 2006

Zubovas & King 2012, 2014
AGN winds and outflows

Fast winds with velocity up to a fraction of $c$ observed in the central regions of AGN. Likely originate from the acceleration of disk outflows by the AGN radiation field.

Crenshaw+03, Pounds+03, Reeves+09, Moe+09

**BAL QSOs** (10-40% of all QSOs)

- Atomic gas makes small fraction of the gas present in a galaxy disk
- Physical scale unknown or small (nuclear)
Galaxy wide outflows of atomic gas

- IFU observations of [OIII] emission of radio galaxies, up to z=2.5 (Nesvabda+ 2006, Swinbank+ 2005, 2006)
  - Extent of broad [OIII] similar to radio emission
  - E_{kin} \sim 1-40\%\ E_{jet}

- SMMJ1237, a QSO in a z\sim 2\ ULIRG (Alexander+ 2010)
  - Extent of broad [OIII] \sim 4-8\ kpc
  - \ E_{\text{kin}} \sim 10^{59}\ \text{ergs over 30 Myr} \sim \text{binding energy of galaxy spheroid}

- Giant SF clumps at z\sim 2\ (Genzel+2011)
  - Broad H\alpha, mass outflow rate > SFR
Galaxy wide molecular outflows

MRK 231

The nearest ULIRG with SFR= 200 M☉/yr late stage merger system hosting a obscured, luminous (BAL) QSO high luminosity ($L_{bol}\sim10^{46}$ erg/s), highly obscured ($N_H\sim10^{24}$ cm$^{-2}$)

Lipari+2009

Carilli+1998

Braito+2004
Galaxy wide molecular outflows: Mrk 231

Narrow component of CO(1-0) + low surface brightness broad component extending out to ±800 km/s
FWZI = 1500 km/s

Spatial resolution

Feruglio et al. 2010

Mass in the OF: \( M(\text{H}_2) > 7 \times 10^7 \, M_\odot \)

Uncertainties due to unknown conversion factor CO-to-H\(_2\)
Galaxy wide molecular outflows: Mrk 231

Size measured $\sim 1$ kpc

Mass loss rate: $\frac{dM(H_2)}{dt} \sim 1000 \, M_\odot/yr$

Mass loss rate larger than the SFR: Gas depletion time of the order $10^7 - 10^8$ yr

No stellar populations younger than $10^6$ years in the central kpc (Lipari et al.)

Kinetic energy of outflowing gas: $E = 1.2 \times 10^{44} \, \text{erg/s} = \text{a few } \% \, L_{\text{Bol}} (5 \times 10^{45} \, \text{erg/s})$ of the AGN

Compatible with models of AGN-driven outflow through a shock wave.

Emission of CO at $+/- 800$ km/s. Mach number is large
If CO is shocked, excitation conditions in the outflow should be different: outflowing gas more excited than low velocity gas.
Neutral gas absorption traces 2-3 Kpc scale outflow with $v \sim 1100$ km/s powered by the AGN

This extended outflow detected in IFU IR observations of neutral gas as well (Rupke et al. 2011)

Neutral gas absorption traces 2-3 Kpc scale outflow with $v \sim 1100$ km/s powered by the AGN

Also a blue-shifted HII region, probably outflow powered by star-formation.

Galaxy wide outflows: Mrk 231

Figure 4: Equivalent width, central velocity, FWHM, and two maps of NaI D. A nuclear outflow extends from the nucleus up to 2-3 kpc in all directions (projected in the plane of the sky). The high velocities suggest that the AGN powers the nuclear wind. The northern quadrant of the nuclear wind is further accelerated by the radio jet. A lower velocity southern driven-outflow is present in the south.
Merging massive BHs: NGC6240

Double AGN
Fe Kα line
~2 kpc separation
Komossa et al 2003

Wang Junfeng et al 2013

Chandra image
NGC6240: a complex system CO outflow

Major merger in early stage of 2 gas rich spirals, with complex morphology, streamers, tidal tails 2 AGN nuclei both heavily obscured, with \( L(2-10) \text{ keV} > 10^{44} \text{ erg/s} \) and \( M(\text{BH}) > 10^8 \text{ M}_\odot \)

H\(\alpha\) nebula with bipolar pattern (east-west): wind sock heating the ISM

H\(2\) emission, tracer of shocked gas

Max et al. 2005
NGC 6240: a complex system with a CO outflow

New sensitive PdBI observations of CO(1-0): broad CO(1-0) detected out to +/- 800 km/s

Central concentration of CO in between the 2 AGN: M(H2) ~ 5 \times 10^9\,\text{Msun}

Blue-shifted extended structures detected on scales of 7\,\text{kpc}

Mass of the central concentration M(H2) ~ 5 \times 10^9\,\text{Msun}

Outflow M(H2) ~ 7 \times 10^8\,\text{Msun}
NGC 6240: a complex system with a CO outflow

CO(1-0) map in velocity channels, high spatial resolution

Feruglio et al. 2013
NGC 6240: a complex system with a CO outflow

Hα nebula traces biconical pattern aligned E-W: super-wind from the southern AGN shock-heats the ISM

CO at -100 kms/ coincides with the dust lane seen in HST image in the S-W region
CO with -400 km/s coincident with Hα filaments in the Eastern region

If CO outflow from the southern AGN, mass loss rate of several 100 M☉ /yr
Spatially resolved spectroscopy with *Chandra*

Analysis of the Chandra X-ray:
evidence for shocked gas at the position of the H$\alpha$ emission, suggests that a shock is propagating eastwards and compressing the molecular gas, while crossing it.

Thermal equilibrium, 2 Temperatures

Thermal + shock, prominent emission lines

Residuals at pos of Mg, Si, S emission
Central concentration of CO in between the 2 AGN
Extended diffuse emission (see Tacconi+1999)
Complex velocity field showing several dynamical components

Stars still bound to the progenitors (Engel 2010)
NGC 6240 nuclear region

Red-shifted gas: concentrated between the 2 AGN

Blue-shifted gas centered on the southern AGN

Previously interpreted as turbulent rotating disk
BUT NOW velocity too large for a rotating disk!

OH absorption: OF with $v_{\text{max}} = -1200 \text{ km/s}$
Veilleux+13
Outflows in the distant universe

Extremely luminous quasar SDSS J1148 at z=6.4
Host galaxy has SFR $\sim 3000$ Msun/yr and $M$(H2) $\sim 2 \times 10^{10}$ M$_\odot$

Broad wings detected in [CII]158um with FWHM = 2000 km/s (Maiolino et al. 2012)

Vmax = 1300 km/s already points towards AGN-driven outflow and shocks

Mof $> 7 \times 10^9$ Msun under conservative assumptions (X(C+), n_crit , Temperature)

Broad component concentrated in the center but extended on scales of 16 kpc

gives mass loss rate of $dM/dt > 3500$ Msun/yr !!!

and kinetic power $P_{kin} > 2 \times 10^{45}$ erg/s

< 1% of the AGN LBol

Well above the power injected by SNa = $\eta$ * SFR * $7 \times 10^{41}$ (\$ \sim 0.1$)

Spatial resolution also at high z to constrain geometry
Summary of AGN extended outflows

Herschel/PACS results + IRAM: statistics

1. Fast OF occurs in the late merger phase
   ULIRG/QSO
2. Driven by AGN
3. Velocity (OH) correlated with 9.7 um silicate absorption (Spoon+13)

Location, geometry, detailed mapping still needed

Remarkable correlation between AGN outflow rate and AGN bolometric luminosity:

\[ \frac{L_{\text{bol}}}{M_{\text{out}}} \approx 7.5 \times 10^{42} \text{ ergs/s} / \text{M}_\odot / \text{yr} \]

Menci model: \[ M_{\text{out}} \approx L_{\text{bol}}^{0.5} \]

King model: \[ M_{\text{out}} \approx L_{\text{bol}}^{1/3} \]
Chemistry of AGN outflows

Most molecular reactions are endothermic, need large activation energy: in GC strong emission of X-ray (6.4 KeV), gamma rays (XDR) and CR

The largest chemical complexity in the MW is close to sgrA*
Feedback, shocks

**SiO** emission (shock tracer) is out of the plane in M82 superwind:
- superwinds expand by shock
- Traces the walls of the supershells - not the SF regions
- Vertical filament - SiO chimney

Also Methanol ~ water on dust grains + shocks

**Noema/ALMA will image shocked regions in many AGN and SF galaxies**

Other shock tracers:
- Methanol  OK from ground
- H2O : only from space for nearby sources
X-ray induced chemistry - AGN diagnostic

The other way round: select obscured AGN by molecular tracers --> then confirm with ATHENA deep observations
NOEMA The northern Extended millimeter array
Project Summary

Upgrade the PdBI:
- double the number of antennas: \( \lambda \rightarrow 12 \)
- double the instantaneous bandwidth: \( \lambda \rightarrow 16 \text{ GHz} \)
- double the baselines: \( \lambda \rightarrow 1.6 \text{ km} \)
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NOEMA: sensitivity @90 GHz

Factor of 2 sensitivity w.r.t. ALMA50 at 3mm continuum

NOEMA ~4x PdBI sensitivity increase in the continuum
~2.3x PdBI sensitivity increase in the line
**NOEMA spatial resolution**

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<th>Source</th>
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<td>1.5 kpc</td>
<td>1.0 kpc</td>
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<sup>a</sup> the angular size distance assumes a flat $\Omega_M = 0.27$ Universe.
Spectral surveys with 16 GHz bandwidth
Redshift searches

→ Systematic studies & surveys that ALMA will not conduct now
Imaging ↔ Simulations @ 100 GHz

M31 (GALEX)

PdBI AB Conf

Boissier 2009
Imaging ↔ Simulations @ 100 GHz

Boissier 2009
Conclusions

What we learnt:

- Molecular outflows common in ULIRG/QSOs, massive & powerful
- Maximum in the late-merger ULIRG/QSO phase
- High velocity + Herschel suggests that the outflow is driven by AGN through shocks (H2O)

What’s next?

Local galaxies:
- Morphology/geometry of galaxy wide outflows
- Assess whether the outflow is driven by a shock, understand the energy transport mechanism from the nucleus to the disk

z=2-3:
- How common AGN feedback at the peak of galaxy/AGN evolution, z=2-3? and beyond
- In which phase of host/AGN evolution does AGN feedback start to be active and how long does the active phase last?

How?

- CO, HCN, ..., NOEMA/ALMA
  CII from SPACE
- Shock tracers: SiO, methanol, ..., NOEMA/ALMA
  + H2O from SPACE only
- Spatially resolved nea-ir and mm spectroscopy
  Sinfoni/VLT, NOEMA, ALMA, E-ELT
  SKA - HI 21 cm line
- Observe large samples/surveys